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STRAIN MEASUREMENTS AND STRENGTH TESTS ON  
THE TENSION SIDE OF A BOX BEAM  
WITH FLAT COVER

By Patrick T. Chiarito and Simon H. Diskin

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ADVANCE RESTRICTED REPORT

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STRAIN MEASUREMENTS AND STRENGTH TESTS ON  
THE TENSION SIDE OF A BOX BEAM  
WITH FLAT COVER

By Patrick T. Chiarito and Simon H. Diskin

SUMMARY

Strains were measured to determine the shear and normal stresses caused by a load applied until failure of the tension side of an open box beam with a flat stiffened cover. The stresses measured at high loads were within 10 percent of the stresses calculated by an approximate theory and also by a method based on an exact theory for all stations except the root, at which the discrepancy was 17 percent. The maximum stress measured on the corner-flange angle was close to the tensile yield stress for the material.

Failure occurred when the corner angle ruptured at a strain of 0.012. This strain was only about 10 percent of the maximum strain that was obtained from tests on solid tensile specimens of the same material.

INTRODUCTION

In order to study the behavior of the compression covers of box beams subjected to bending, several tests have been performed at the Langley Memorial Aeronautical Laboratory. The results of these tests and the analysis of the stresses by an approximate shear-lag theory are presented in references 1 and 2. In general, the calculated values of the stresses were in fair agreement with the highest experimental values, which occurred at the corner flanges of the box beams.

The phenomenon of failure in the tension side has been studied in the present investigation. Normal stresses

in the cover were obtained from strain measurements at several cross sections for loads up to 95 percent of the ultimate load. Shear stresses in the cover sheet were obtained from strain measurements for low loads (21 percent of the ultimate load).

The existing knowledge of stress concentration is not sufficient to explain satisfactorily the influence of rivet holes on the tension failure in a built-up structure. The first step toward a satisfactory explanation of failure is the detailed determination of the stress distribution in that part of the structure which fails first. In order to substantiate the strain measurements on the corner angle of the box beam, strains were also measured on auxiliary specimens that resembled the corner angle.

#### SYMBOLS

A cross-sectional area, square inches

$A_F$  cross-sectional area of idealized corner flange, square inches

$A_L$  cross-sectional area of substitute single stringer, square inches

$A_T$  sum of  $A_F$  and  $A_L$ , square inches

P total external applied load, kips

L length of half beam, inches

$$K = \sqrt{\frac{Gt}{Eb_S} \left( \frac{1}{A_F} + \frac{1}{A_L} \right)}$$

G shear modulus, ksi

E Young's modulus of elasticity, ksi

t thickness of cover sheet, inch

$b_S$  width of substitute half beam, inches

$M_z/I$  normal stress defined by engineering theory of bending, ksi

- M bending moment, kip inches
- z distance from centroidal axis to a given fiber, inches
- I moment of inertia of effective cross section of box beam about centroidal axis, inches<sup>4</sup>
- $VQ/It$  shear stress defined by engineering theory of bending, ksi
- V vertical shear in web, kips
- Q static moment or moment of area (between center line and panel for which shear stress is to be determined) about centroidal axis of box beam, inches<sup>3</sup>
- h effective depth of beam, inches
- x distance from tip of beam, inches
- $\tau$  shear stress, ksi
- $\epsilon$  strain
- $\sigma_F$  normal stress in idealized corner flange, ksi

## Subscripts:

ult ultimate

ty tensile yield

## EXPERIMENTAL INVESTIGATION

## Specimens and Apparatus

An open box beam was tested to failure of the tension cover. Three auxiliary specimens were also tested: auxiliary specimen A was used for measurements of strain up to failure in angles similar to the corner-flange angle of the beam; specimen B was used to study the influence of a single line of rivet holes on the distribution of strains in a flat bar; and specimen C was tested to obtain some idea about the possible strains caused by riveting.

Box beam.- The details of the cross section of the box beam are shown in figure 1(a). The beam was made of 24S-T aluminum alloy with the exception of the compression chord and the bulkheads, which were steel. An extruded angle joined the cover sheet to the shear webs by means of  $\frac{3}{16}$ -inch rivets spaced at  $\frac{3}{4}$  inch. All the rivets used in the box were of Al7S-T aluminum alloy. The bulkheads were located as shown in figure 1(b).

Auxiliary specimens.- Auxiliary specimen A was a double-angle, riveted tension specimen made of two 24S-T angles 1- by 1- by  $\frac{3}{32}$ -inch and joined at both ends to a common steel loading bar 1-inch square. These angles and the riveting in them were similar to those used in the corner of the box beam. Figure 2 shows specimen A after failure occurred at the left-hand end of the test section.

Auxiliary specimen B was made from a  $\frac{1}{8}$ - by  $\frac{3}{4}$ -inch flat bar of 24S-T aluminum alloy. Seven  $\frac{3}{16}$ -inch round-head rivets of Al7S-T aluminum alloy were spaced at  $\frac{3}{4}$ -inch intervals along the longitudinal center line.

Auxiliary specimen C consisted of an angle 1- by 1- by  $\frac{3}{32}$ -inch of 24S-T aluminum alloy. The rivet holes simulated those used in the test section of specimen A, as well as those in the corner angle of the box beam. The rivets, however, were merely inserted in these holes and were not driven before the test.

Apparatus.- For the test at low loads, an A-frame was used to support the box beam at the center line and the load was applied by a winch and measured by a 5-kip-capacity dynamometer at each tip of the beam. (See fig. 3.) In this way the closest possible approximation to a fixed root was realized. With the cover sheet in a vertical plane, it was most convenient to read the optical strain gages mounted on both sides of the cover.

For the strength test, the beam was supported with its cover in a horizontal position and was anchored to

the floor through four steel straps that were attached to the tips of the shear webs. (See fig. 4.) A portable hydraulic jack of 100-kips capacity was used to apply load through a yoke at the center line of the doubly symmetrical box. A fixed root again was closely approximated.

Auxiliary specimens A and B were tested in standard hydraulic testing machines.

### Test Procedure

Strain measurements on box beam.— For the tests that were confined to the elastic range, strains were measured by Tuckerman optical strain gages with a gage length of 2 inches. In order to reduce the effect of local bending, the gages were used in pairs on both sides of the cover except on the corner angles. Typical strain-gage locations used in the four quadrants of the cover are shown in figure 5(a). The load was applied in a minimum of three equal increments up to the maximum of 1.5 kips at each tip of the beam. If the straight line through the points on the load-stress plot for each pair of gage measurements did not pass through the origin, the line was so translated as to pass through the origin. If the necessary translation corresponded to more than 0.2 ksi, however, the test was repeated and new data were obtained. For determining shear stresses, strains in the cover sheet were measured at  $45^\circ$  and  $135^\circ$  to the longitudinal axis between the station  $4\frac{1}{2}$  inches from the root and the station  $6\frac{1}{2}$  inches from the tip. Strain measurements on the stringers and corner angles were confined to the vicinity of the root, where the maximum normal strains were expected.

For the test to failure, strains were measured with SR-4 electrical strain gages of three different gage lengths: 1 inch,  $\frac{1}{2}$  inch, and  $\frac{1}{4}$  inch. Figure 5(b) shows typical locations of the SR-4 gages in the cross section. Longitudinal strains were measured in the corner angle for ten loads within the elastic range. Beyond the elastic range, measurements were made after each application of a small load increment (about 5 percent of the ultimate load) up to the jack load of 13.2 kips

(95 percent of the ultimate load). No attempt was made to measure the shear stresses in the cover sheet at high loads. The loading of the box beam was accidentally interrupted at 12.6 kips and the load was entirely removed. When the loading was resumed, strain readings were taken at 12.6 and 13.2 kips.

In order to reduce thermal errors in the measurements by the Tuckerman and SR-4 gages, a reasonable amount of control was exercised over the temperature in the vicinity of the test specimens.

Strain measurements on auxiliary specimens.- The perforated specimen A was tested in tension in an attempt to measure strains at gage locations that corresponded to those used on the corner angle of the box beam. Gage readings were taken after each application of a load increment that was about 7 percent of the ultimate load.

Strain measurements were made between rivets and along the edges of the flat-bar specimen B. Gages with an effective length of approximately  $\frac{1}{4}$  inch were used in pairs on opposite sides of the specimen to measure the strains while the tensile load was increased in increments of approximately 6 percent of the ultimate load.

Strains resulting from the riveting process were measured on the angle specimen C at locations similar to those on the corner angle. The rivets were driven with a pneumatic hammer to simulate the riveting process used in the construction of the box beam. No external load was applied to specimen C.

Accuracy of measurements.- The thicknesses of all parts made from 24S-T aluminum-alloy sheet were obtained by micrometer caliper measurements with an accuracy of about 0.0002 inch. The areas of the 24S-T alloy angles and the steel compression-chord angles were obtained by weighing and are probably not in error by more than 0.5 percent. The loads applied by either the hydraulic jack or the testing machines were measured with an accuracy of about 0.5 percent.

Strains were measured to 0.000002 with the Tuckerman optical strain gages. Strains measured with the SR-4

electrical strain gages were accurate to 0.00002 for strains up to 0.001; for larger strains the error was probably not more than 2 percent.

### Properties of Materials

The stress-strain curves for the materials used as corner-flange angles, stringer, and cover sheet were obtained from tensile tests on solid standard specimens and appear in figure 6. Figure 6(a) represents four tests, and figures 6(b) and 6(c) represent two tests each. The yield stress of 54.5 ksi, shown by figure 6(a), is appreciably higher than the typical value of 49.0 ksi shown by figure 3 of reference 3. The curves in figures 6(b) and 6(c) are in good agreement with the corresponding curve marked W in figure 1 of reference 3. The similarity of the three stress-strain curves reduced the uncertainty that usually accompanies the determination of the stress distribution in structures built up from materials which do not have identical physical properties.

The stress-strain curve for the material of the double-angle specimen A is shown in figure 7 and is the average for two tests. The yield stress of 47.0 ksi was in good agreement with that given by curve A in figure 3 of reference 3. No stress-strain curves were obtained for auxiliary specimens B and C.

### TEST RESULTS AND COMPARISONS WITH CALCULATIONS

The measured strains were converted to stresses by use of the stress-strain curves obtained from tension tests on solid standard tensile specimens (figs. 6 and 7). Because the strains varied within the dimensions of the gages, the experimental stresses represent averages over the areas covered by the strain gages. In order to interpret more exactly the measured strains, additional information is required about the effect of the rivet holes on the measurements and the conversion of these strains to stresses, especially in the plastic range. In order to explain the failure, a knowledge of the distribution of stress throughout the components of the beam is necessary.



### Stress Distributions

In the following presentation of test results, the averages of the stresses indicated by pairs of opposite gages were used to obtain the average of the stresses for corresponding stringers on each side of the longitudinal center line of the cover. The individual strain measurements were converted to stresses before the averages were obtained. These averages were usually within 2 percent of the individual measurements; the maximum difference noted was 5 percent.

The stresses measured on the outside of the cover only (at the root) are shown on the plots by the appropriate symbol with two tails added. The stresses measured at only one of a pair of corresponding stations - that is, in one quadrant of the cover - are represented by the appropriate symbol with one tail added. In general, a symbol without a tail represents the average of four measurements.

Because the depth of the flange angles (on the compression as well as the tension sides) was large in comparison with the depth of the beam, the effective depth of the beam was taken as the distance between force centroids. The approximate analysis of the stresses in the cover was made by the substitute single-stringer method of reference 4. Figure 8 shows the steps used for obtaining the substitute single-stringer structure from the actual cross section.

An analysis was also made based on an adaptation of the exact method and on the comparison between the approximate and exact methods as shown in figure 6 of reference 5. In both analyses, the stresses were distributed among the stringers by the cubic-equation method of reference 6.

Shear stresses at low loads.- Strains were measured on the cover sheet at  $45^\circ$  and  $135^\circ$  to the stringers and were then converted to shear stresses by use of the relationship

$$\tau = G (\epsilon_{45} - \epsilon_{135}) \quad (1)$$

The curves of figures 9(a) and 9(b) show the spanwise and chordwise distributions, respectively, of these shear stresses at a total load of 3.0 kips or 750 pounds at each tip of the shear webs. The distributions calculated by the elementary formula  $\tau = \frac{VQ}{It}$  are shown, as well as the curves calculated by the shear-lag theory. The spanwise distribution of the shear stresses in panel 1 next to the corner flange was calculated by use of the following equation derived from reference 7:

$$\tau_1 = \frac{PA_L}{thA_T} \left( 1 - \frac{\cosh Kx}{\cosh KL} \right) \quad (2)$$

The shear stresses decreased gradually to zero at the root. Because the stringer areas were equal and uniformly distributed chordwise along the cover sheet, the chordwise stress distribution near the tip calculated by the ordinary engineering theory  $\frac{VQ}{It}$  was approximately a straight line that varied from  $\tau_1$  (see equation (2)) at the outer panel to zero at the center line. The shear stress at the center line was zero throughout the span of the beam because of the symmetry of the cross section and loading. Although the engineering theory of bending did not apply rigorously in the vicinity of the root, the simplifying assumption of linear chordwise distribution of shear stresses gave satisfactory values. The exact distribution at the root, moreover, was of little practical importance because the shear stresses approached zero. The calculated stresses agreed with the measured values within about 10 percent and were conservative for all stations.

Normal stresses at low loads.— The spanwise distribution of normal stress in the corner flange was calculated by the following expression derived from reference 7:

$$\sigma_F = \frac{Mz}{I} \left( 1 + \frac{A_L}{A_F} \frac{\sinh Kx}{Kx \cosh KL} \right) \quad (3)$$

The stringer stresses were obtained by the method outlined in reference 6.

The analysis of the normal stresses was also made by the approximation based on the exact method of reference 5. Interpolation between the appropriate curves of figure 6 in reference 5 gave the ratio between the approximate and exact stresses at the root. This ratio was used as a guide in calculating the "exact" spanwise distribution of corner-flange stress so that this "exact" curve would be related to the approximate curve in the same manner as the exact curve is related to the approximate curve for flange stress in figure 4 of reference 5. The chordwise distribution was made as before by use of the cubic-equation method of reference 6.

The values of the stringer stresses, which were measured with the optical gages and the electrical gages, agreed with the calculated values within about 10 percent for all stations except the root at an applied load of 3.0 kips. For this load, the maximum discrepancy between experimental and calculated values at the root was about 30 percent. A large discrepancy was expected because measurements were made on the outside of the beam only (because of interference by the bulkhead). These single measurements served to indicate maximum stringer stresses, which probably include secondary bending stresses. At the flanges the measured stresses were, on the whole, about 15 percent lower than the calculated values.

The chordwise distribution of stresses measured with electrical strain gages at a jack load of 6.0 kips (43 percent of the ultimate load) or 1.5 kips at the tip of each shear web is compared with calculated values in figure 10. The average measured stress in the corner angle was, at all stations, about 15 percent lower than the stress calculated by the approximate theory and about 11 percent lower than the stress calculated by the adaptation of the exact theory. In general, the values of the stringer stresses agreed within about 15 percent.

Although large discrepancies were noted between experimental values and the calculated curves, the summation of the internal forces balanced the external force  $M/h$  within about 10 percent.

Normal stresses at high loads.- In figure 10 the measured stresses and calculated curves at the jack load of 12.6 kips (91 percent of the ultimate load) are shown. The average of the measured stresses in the corner angle

at each station was within 10 percent of the calculated values at all of the stations except the root, at which the average measured value was about 17 percent lower than the approximate value and 12 percent lower than the "exact" value. If the root station is neglected, the measured stresses in the corner angle are within 5 percent of both the approximate and the "exact" values. The stringer stresses were within 11 percent of the calculated values at all stations except the root. As was previously mentioned, the single measurements at the root probably include secondary bending stresses. The summation of the internal forces at all stations balanced the external load within 3 percent.

Figure 11 shows the spanwise distribution of measured and calculated stresses at several values of jack load. The lowest measured value at the root can probably be explained as the result of the measurement of strain between rivet holes. This explanation is supported by the results of later tests that are discussed herein under "Auxiliary tests." The spanwise readjustment of flange stresses, which is evident at the load of 12.6 kips, can probably be attributed to the two following causes: (1) The buckling of the cover sheet in panel 1 reduced the effective shear modulus with the resulting increase in the flange stresses (because of increased shear-lag effect); and (2) the yielding of the flange material decreased the ability of the flange to carry additional load. The test data indicate that the effect of yielding might become appreciable. Additional information must be obtained, however, before a suitable correction for yielding may be devised.

The load-strain plots of figure 12 resemble stress-strain curves. The measured strains were expected to lie along a smooth curve. The irregularity in the load-strain plots of the highest measured strain might be explained by the behavior of the structure following the interruption in the loading, as mentioned under "Test Procedure." The superposed load-stress points emphasize the tendency for the stresses not to exceed appreciably the tensile yield stress of 54.5 ksi.

Auxiliary tests.— The load-strain curves for the double-angle specimen A shown in figure 13 resemble the curves for the corner-flange angle shown in figure 12. Because the loading was continuous, however, the plotted

strains lay along a smooth curve. As was the case for the corner angle, the stresses in auxiliary specimen A were approximately equal to the yield stress of 47.0 ksi.

The strains measured on the flat-bar specimen B in the vicinity of rivet holes might differ by about 100 percent as shown in figure 14. The maximum strain occurred between the rivet hole and the edge of the bar. The minimum strain was measured between rivets. Because the gage length used was about 1/4 inch and the width of gage was about 1/8 inch, the measured strains are most likely not the peak strains. The unusually low strains measured between rivets probably explain the low values obtained from the measurements at the root station of the box beam between rivets on the corner angle. (See fig. 11.)

The maximum stresses caused by riveting, as indicated by the test on auxiliary specimen C, were about 2500 psi and occurred at gage locations between rivets and the heel of the angle. These stresses were of the order of magnitude of the differences between test points at the root. The rivets in specimen C differed from those in the corner angle in that those in specimen C were driven through a single thickness and were not countersunk.

### Strength Test

Failure of box beam.- The corner-flange angle broke at the root when the jack load reached 13.9 kips. Tearing of the cover sheet and stringers followed immediately and extended over about 80 percent of the chord. As shown in figure 15, the tear in the cover did not occur along the root station, where the net section was reduced by the bulkhead rivets.

Strength of corner flange.- Extrapolation of the load-stress plots of figure 12 from the jack load of 13.2 kips to the ultimate load of 13.9 kips indicated that the maximum stress in the corner flange was approximately 55.0 ksi. This extrapolated stress was 19 percent lower than the stress calculated for the ultimate load by the approximate shear-lag theory (65.5 ksi) and 13 percent lower than the value calculated by the "exact" method (62.2 ksi). For both calculations, Young's modulus of elasticity was assumed to be constant. The extrapolated ultimate strain for the flange of the box beam was

about 0.012, whereas the corresponding strain in the double-angle specimen was about 0.015. This discrepancy was probably due to the differences in conditions of support along the angle, in methods of loading, and in riveting. The maximum strain that was measured in the corner flange of the box beam was only about 10 percent of that obtained from the tests on the solid standard tensile specimens.

Strength of cover sheet and stringers.- The values of ultimate stress, which resulted from extrapolation of load-stress plots, were approximately 55.0 ksi for the sheet and 53.8 ksi for the stringers. The yield stresses determined from tests on solid standard tensile specimens were 55.0 ksi for the sheet and 53.5 ksi for the stringers. (See fig. 6.) Although the highest strains measured in the cover sheet and stringers were at the root station, the tear extended from the corner angle to the center line at approximately one inch from the root. Beyond the center line, the tear continued towards the other corner angle at about three inches from the root.

#### CONCLUDING REMARKS

In the test of the flat stiffened tension cover of an open box beam, the stresses measured at high loads were within 10 percent of the calculated stresses for all stations except the root, at which the average measured value was about 17 percent lower than the value calculated by the approximate shear-lag theory and 12 percent lower than the value obtained by an adaptation of the exact method. When the normal stress in the flange reached the yield stress for the material and after the cover sheet in the outer panels had buckled, a spanwise readjustment of flange stress took place. The shear stresses in the cover sheet were calculated to within 10 percent of the measured values.

The extrapolated ultimate strain in the corner-flange angle at the root of the beam was approximately 0.012, whereas 0.015 was obtained for a double-angle tension specimen of the same cross section. These values were only about 10 percent of the maximum strains that were measured in gage lengths of 2 inches on standard tensile specimens of solid cross sections. These values provide

an index of the maximum elongation of the corner flange of the box beam in comparison with the values for the standard tensile specimens.

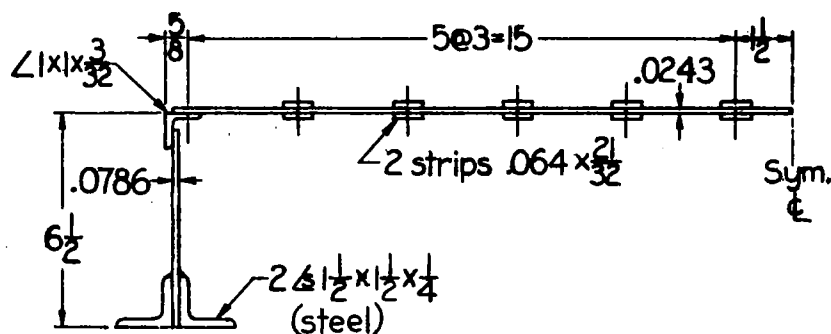
The variations in strains measured at different locations on the beam and the double-angle specimen A emphasized the fact that doubt still accompanies the interpretation of strains measured in riveted structures. Because the strains in the beam varied within the dimensions of the gages, the measured strains represent averages over finite areas. In order to interpret more exactly the strains measured up to failure, it is necessary to obtain additional information about the influence of rivet holes. The interpretation of strain measurements is made uncertain also by the existence of built-in strains caused by riveting.

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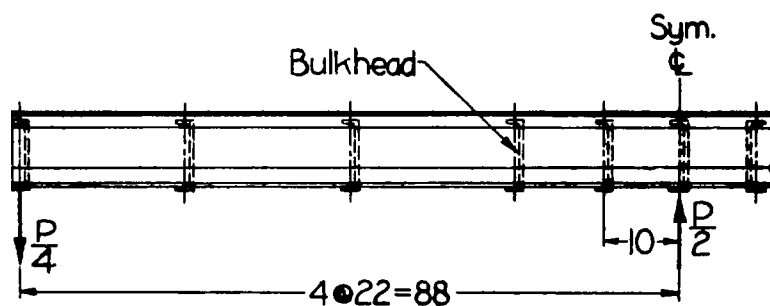
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(a) Cross section of box beam.



(b) Half span of box beam with tip load.

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Figure 1.-Dimensions of test beam.

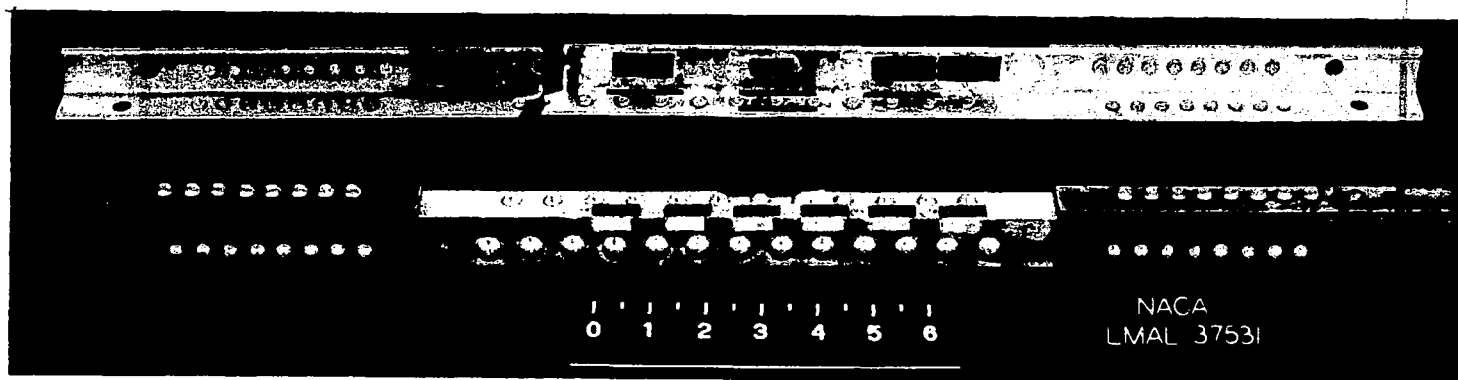


Figure 2.- Angles used in auxiliary specimen A. (Note failure.)

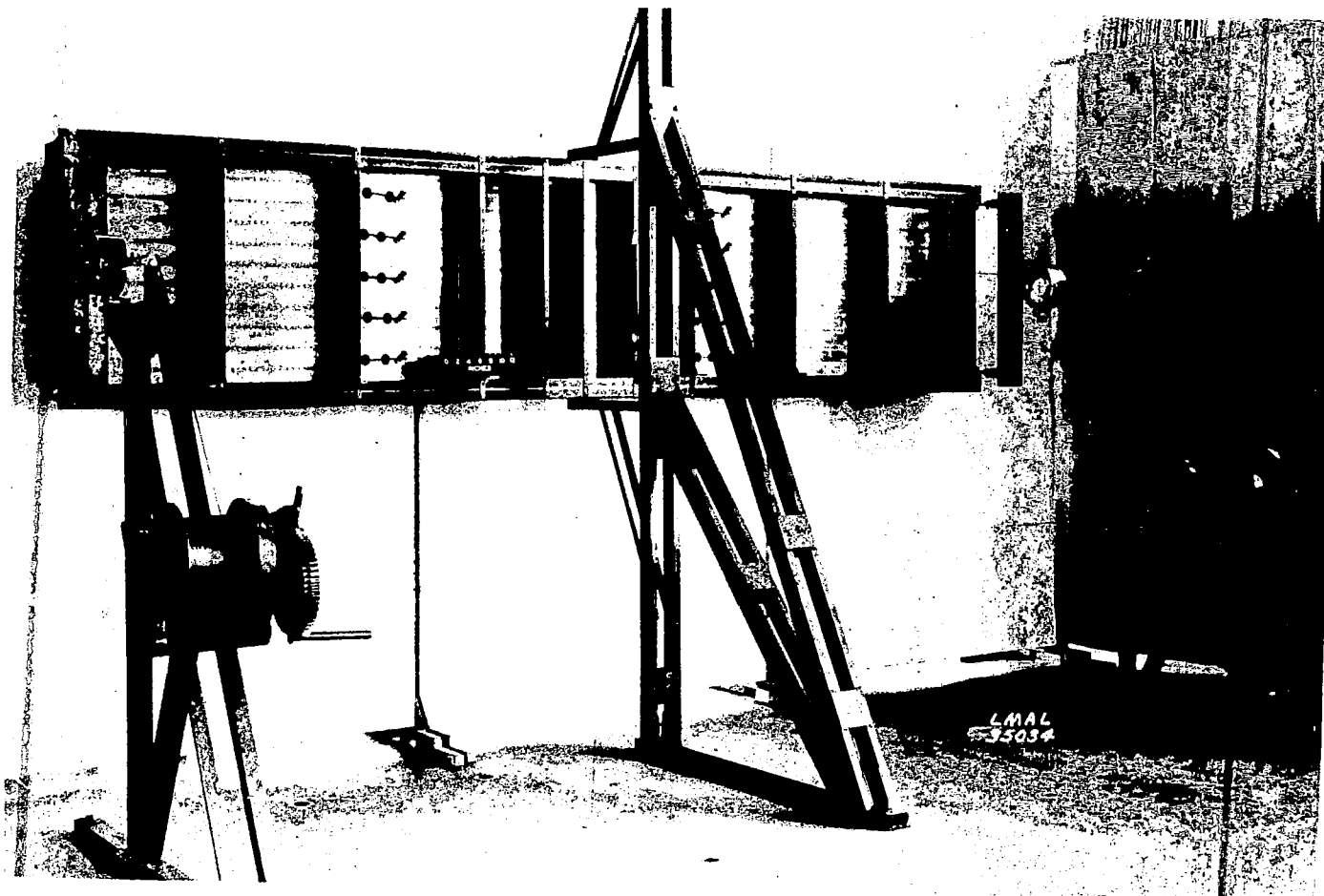


Figure 3.- Setup for tests at low loads.

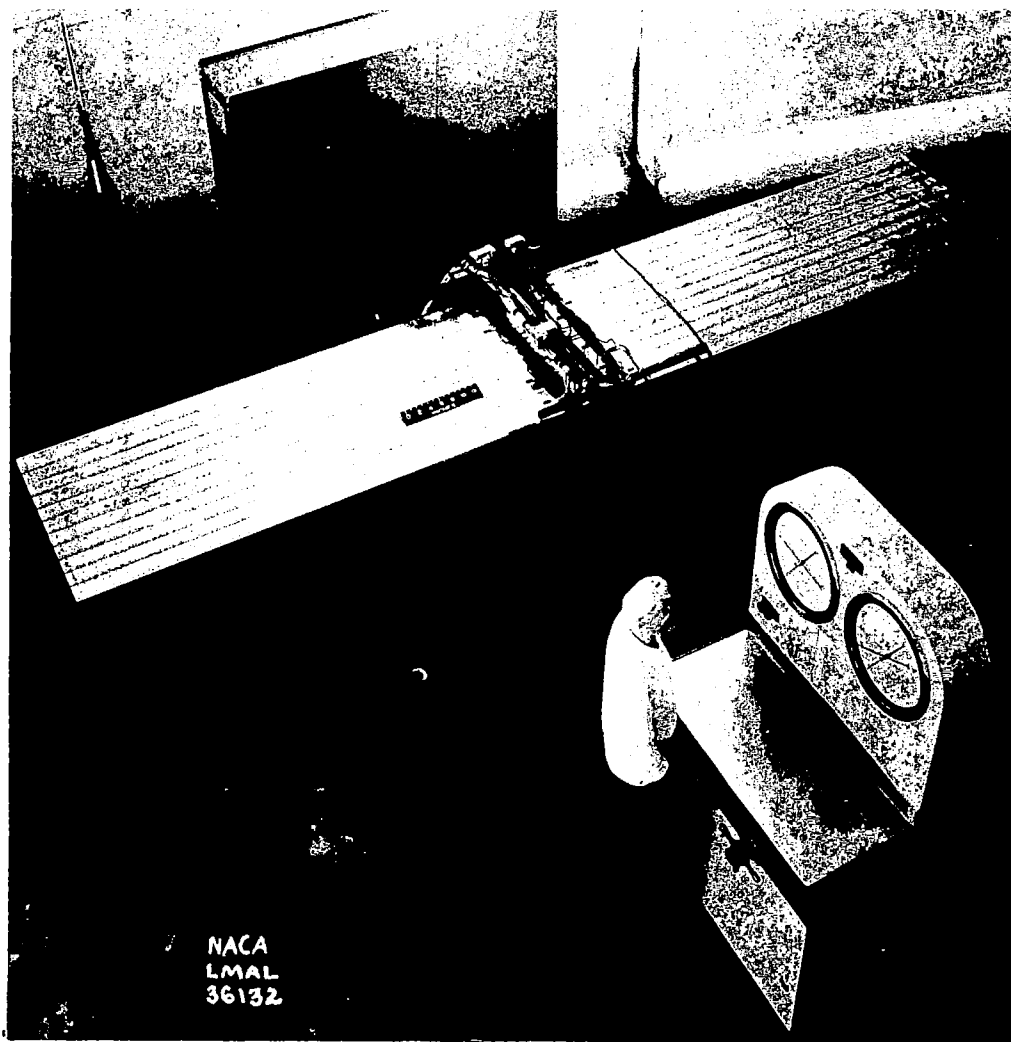


Figure 4.- Setup for strength test.



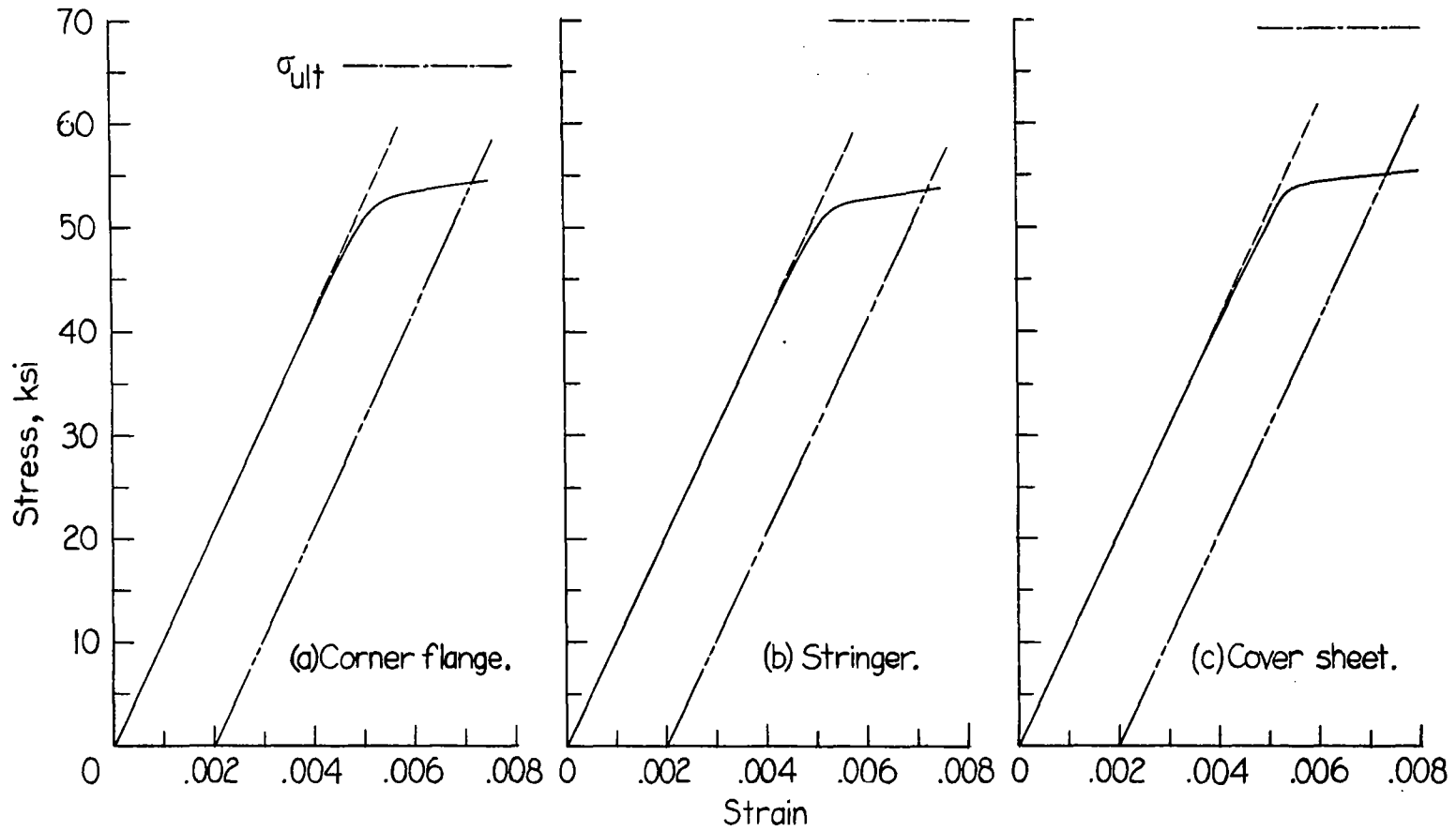
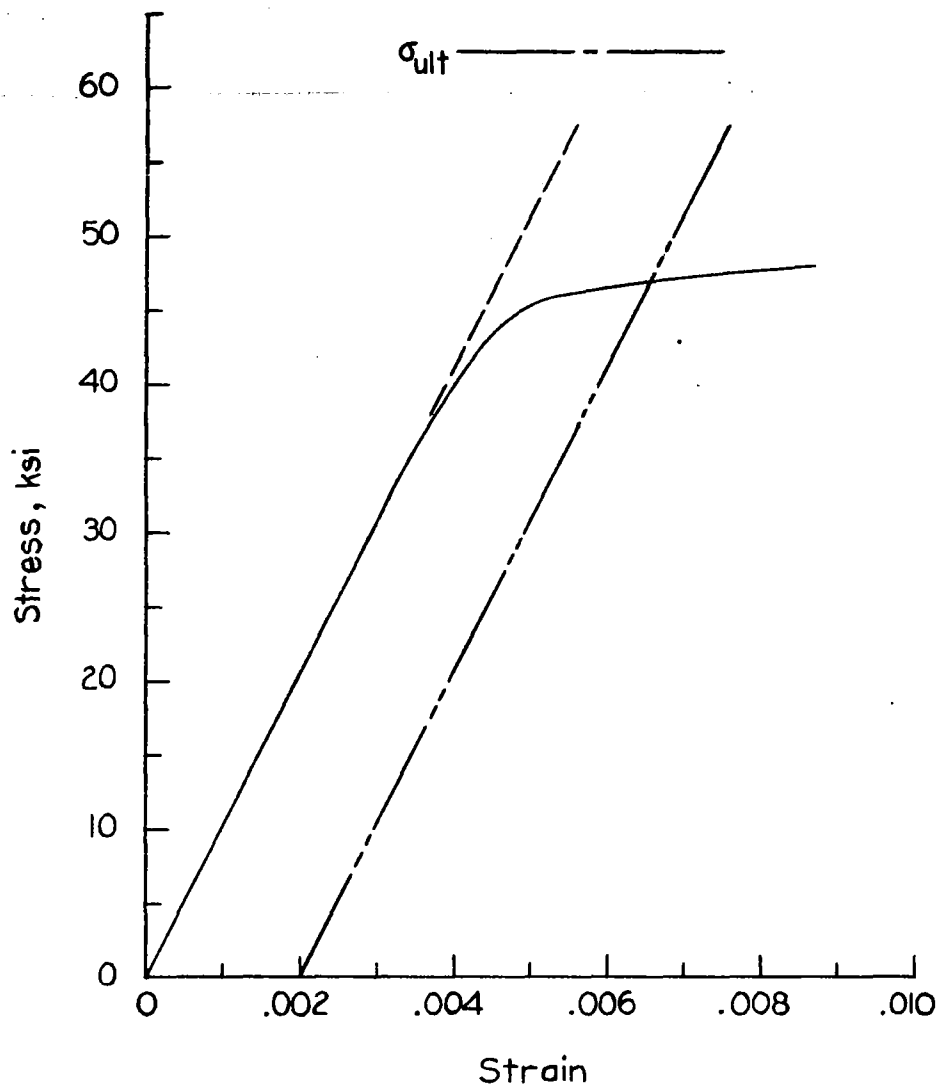


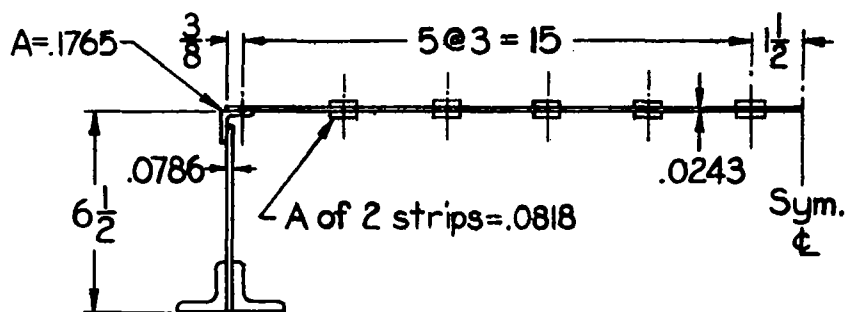
Figure 6.-Tensile stress-strain curves for 24S-T cover materials.

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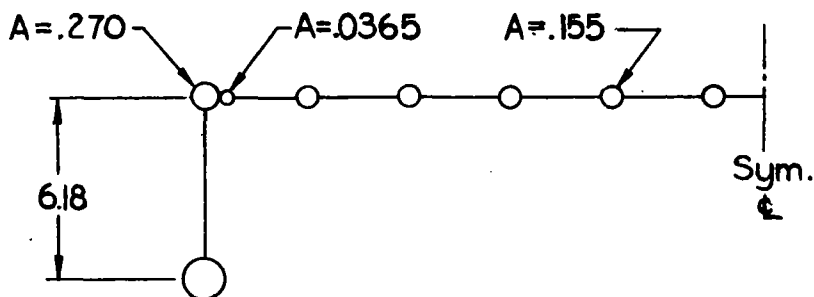


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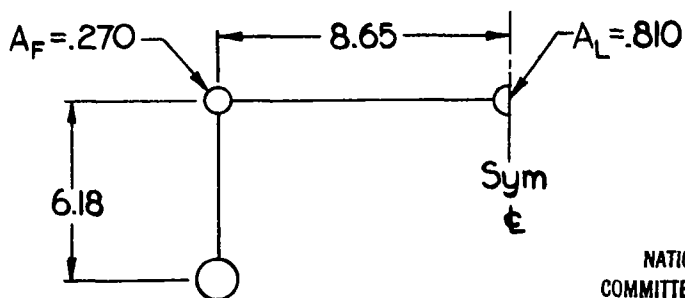
Figure 7.-Tensile stress-strain curve for 24ST material used in specimen A.



(a) Actual cross section.



(b) Idealized cross section.

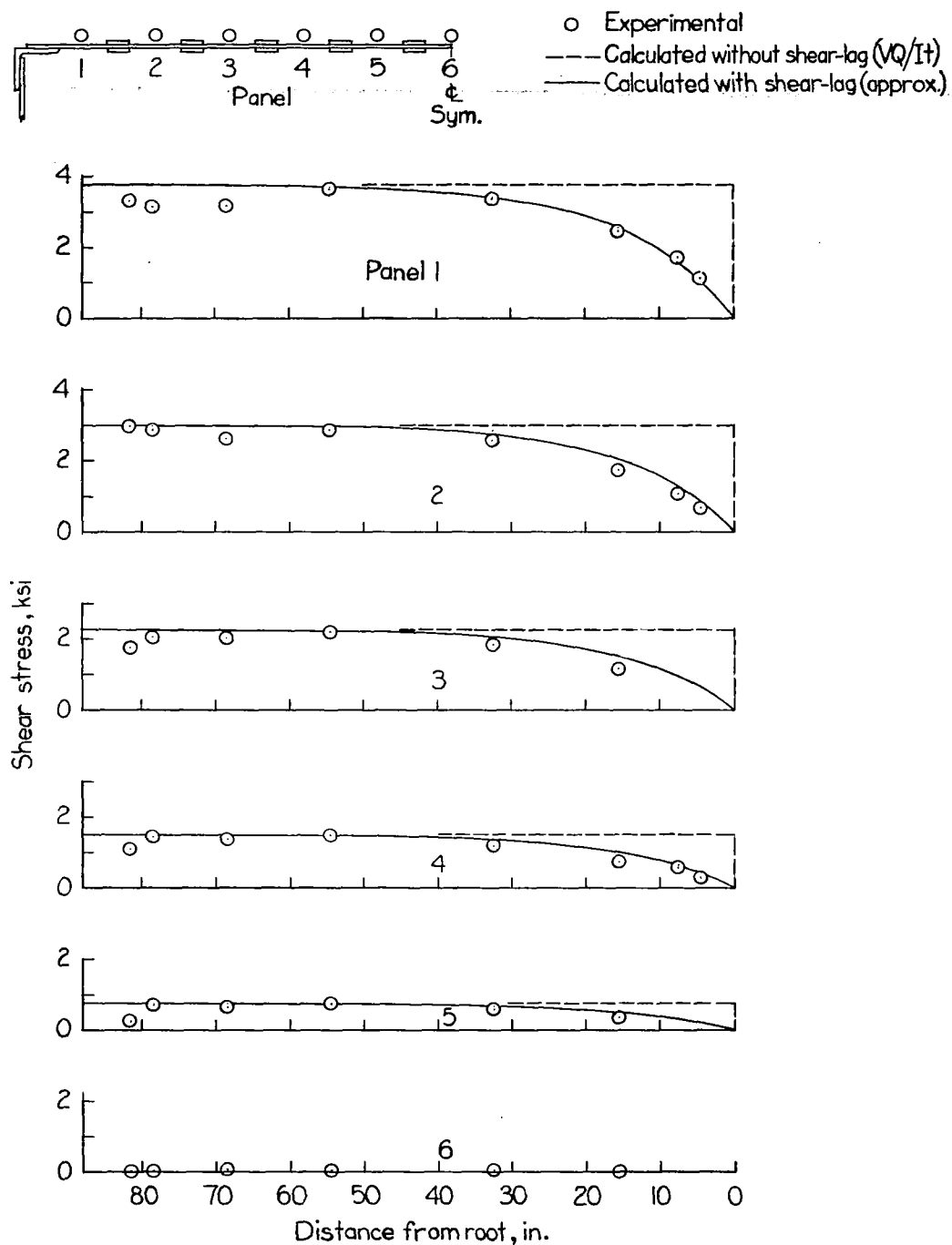


(c) Substitute single-stringer beam.

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Figure 8.-Idealization of cross section of box beam.



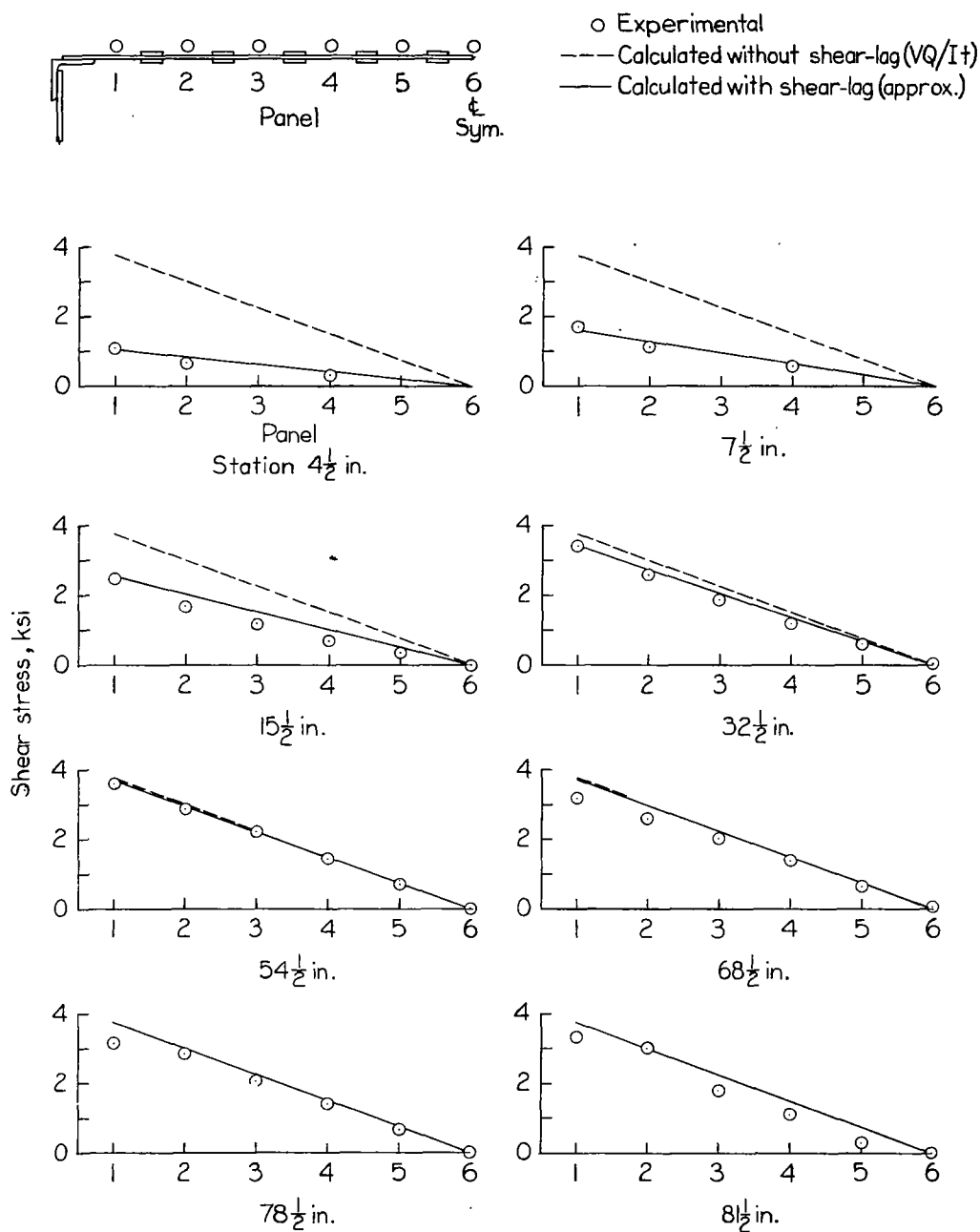
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(a) Spanwise distribution.

Figure 9.—Shear stresses in cover;  $P=3.0$  kips.

Fig. 9b

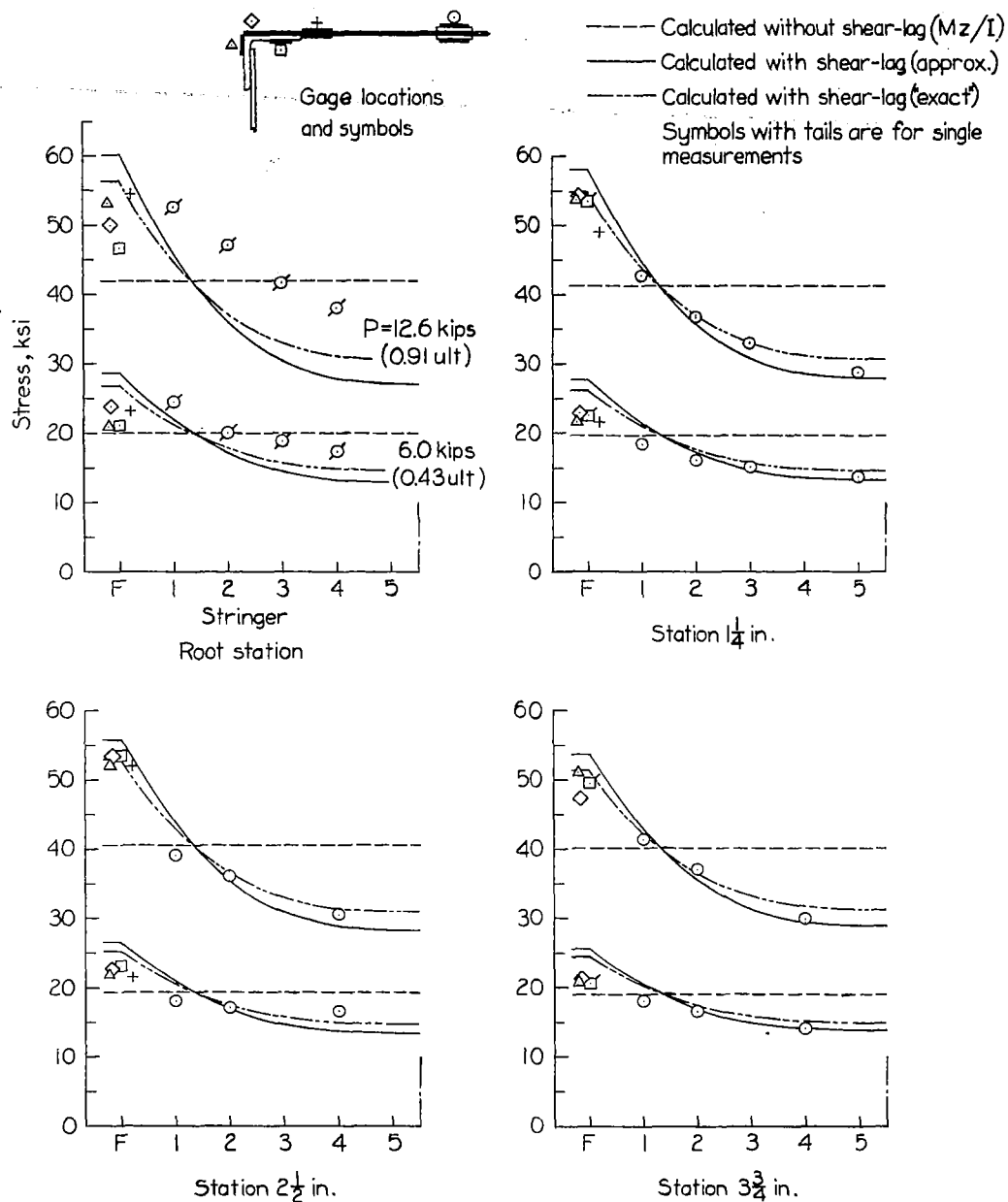
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(b) Chordwise distribution.

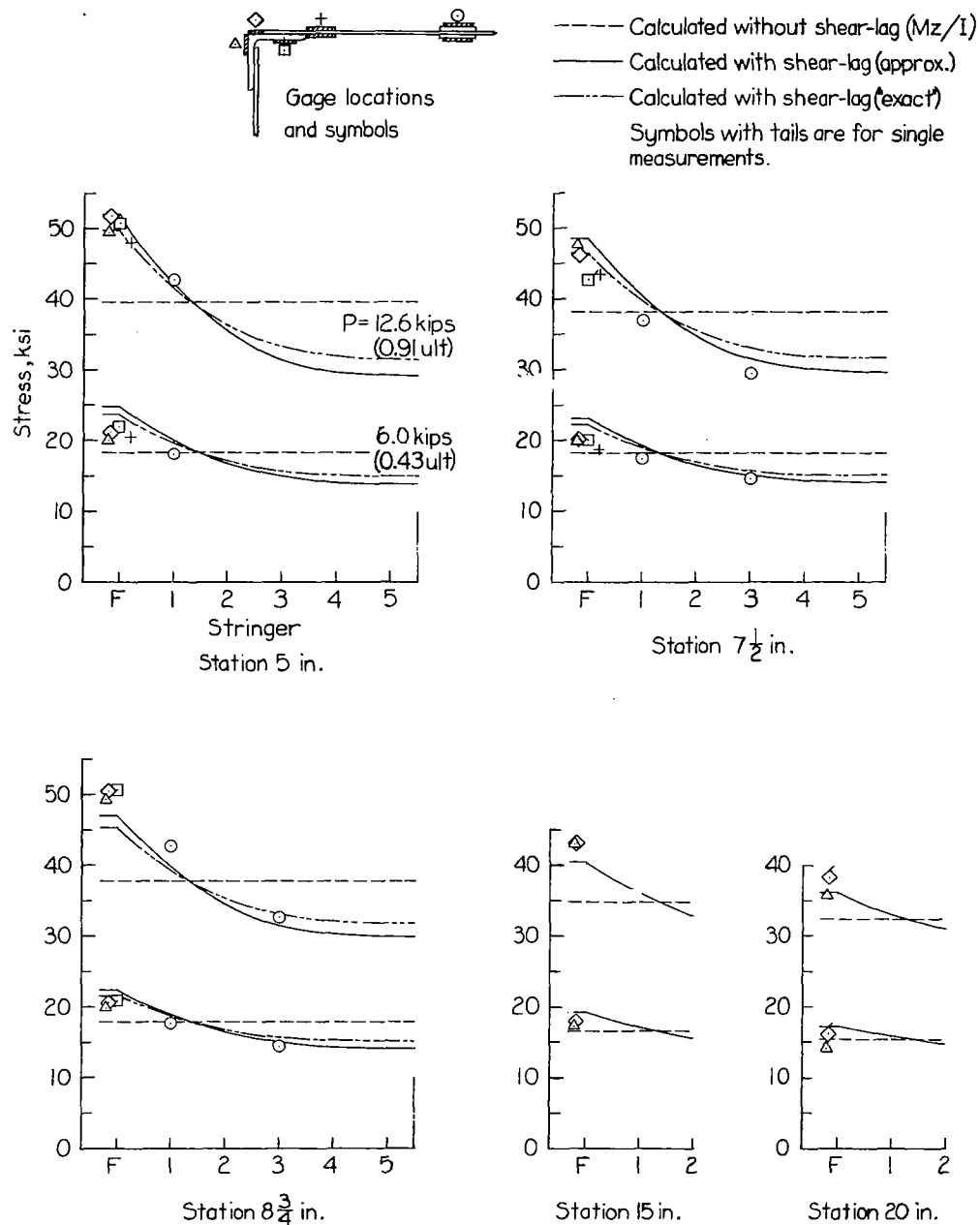
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Figure 9.-Concluded.



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Figure 10.—Chordwise distribution of normal stresses in cover;  $P$  = Jack load.



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Figure 10.- Concluded.

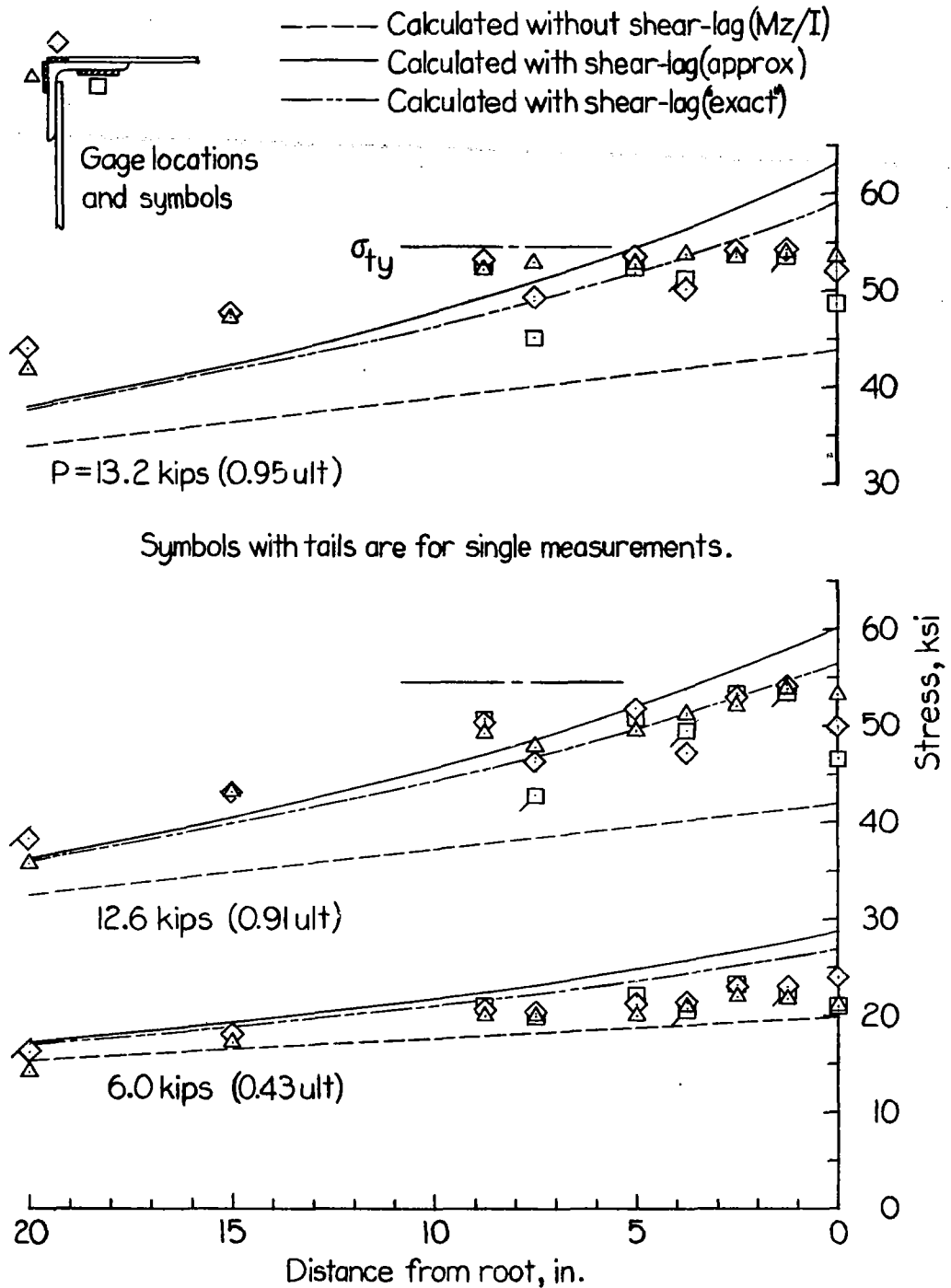


Figure 11.— Spanwise distribution of normal stresses in corner flange;  
 $P =$  Jack load.

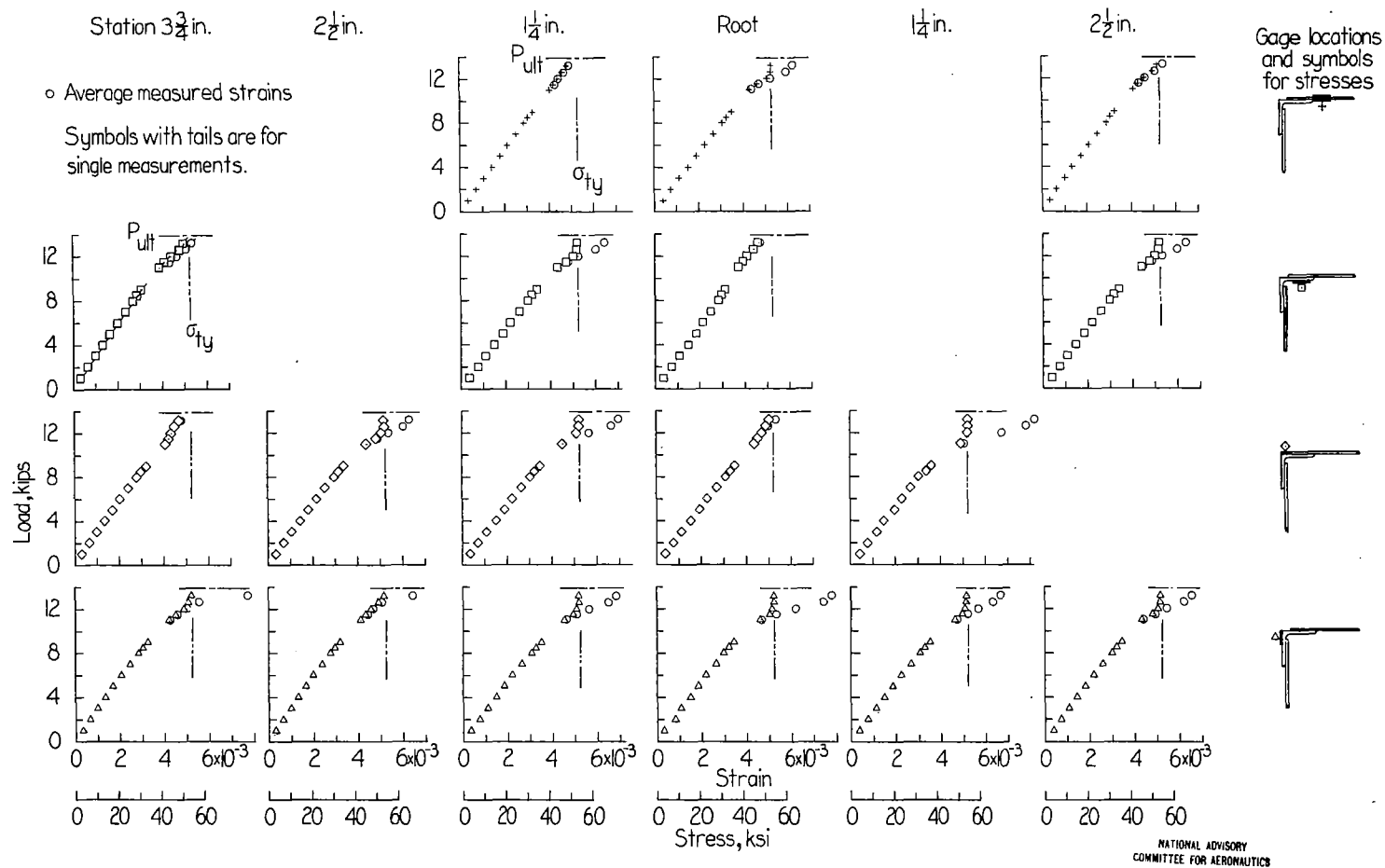


Figure 12.- Variation of measured strain and stress with applied load at gage stations on the box beam in the immediate vicinity of the failure.  
(Note that values at maximum load are doubtful because loading was interrupted.)

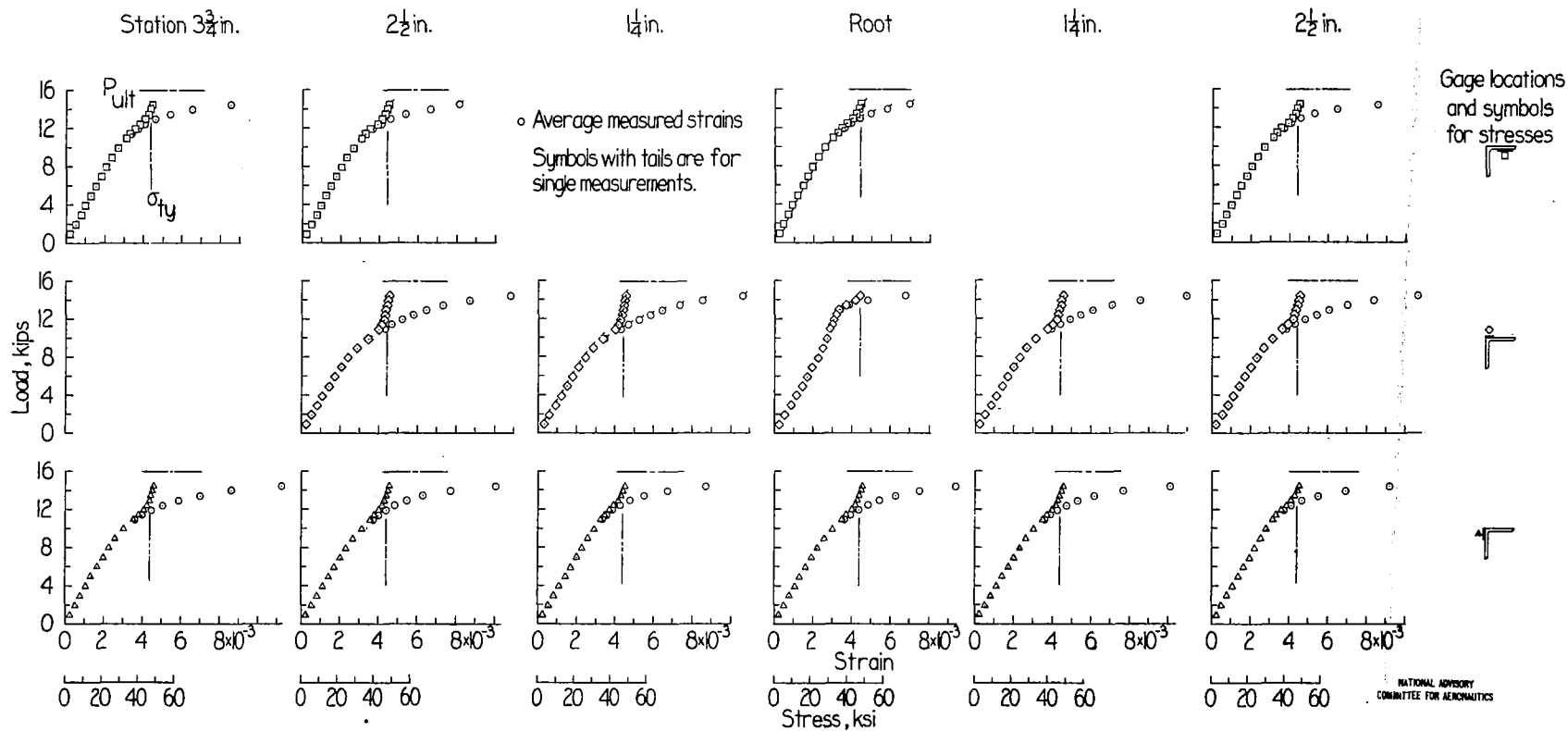


Figure 13.- Variation of measured strain and stress with applied load at gage stations on the double-angle riveted tension specimen A.

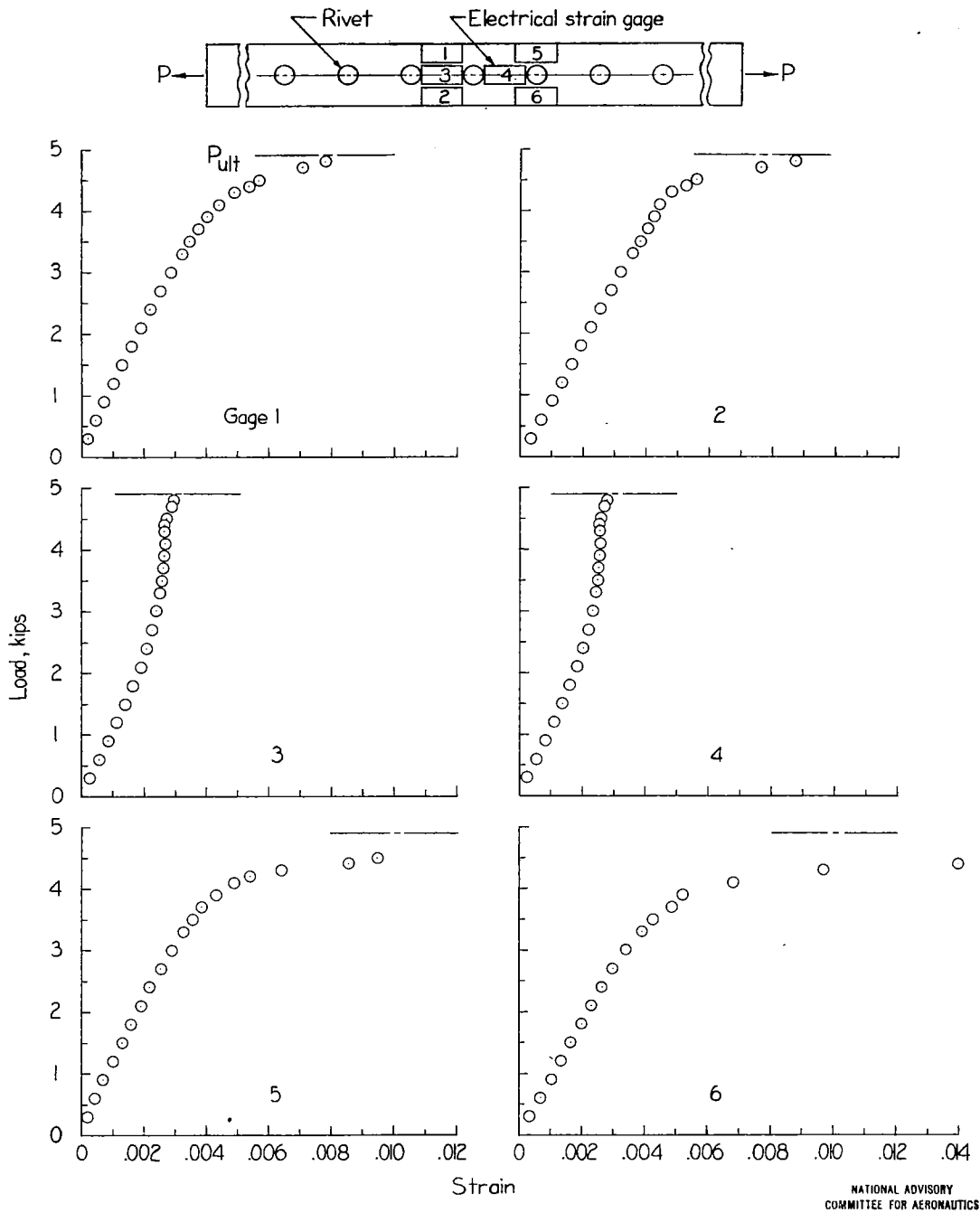
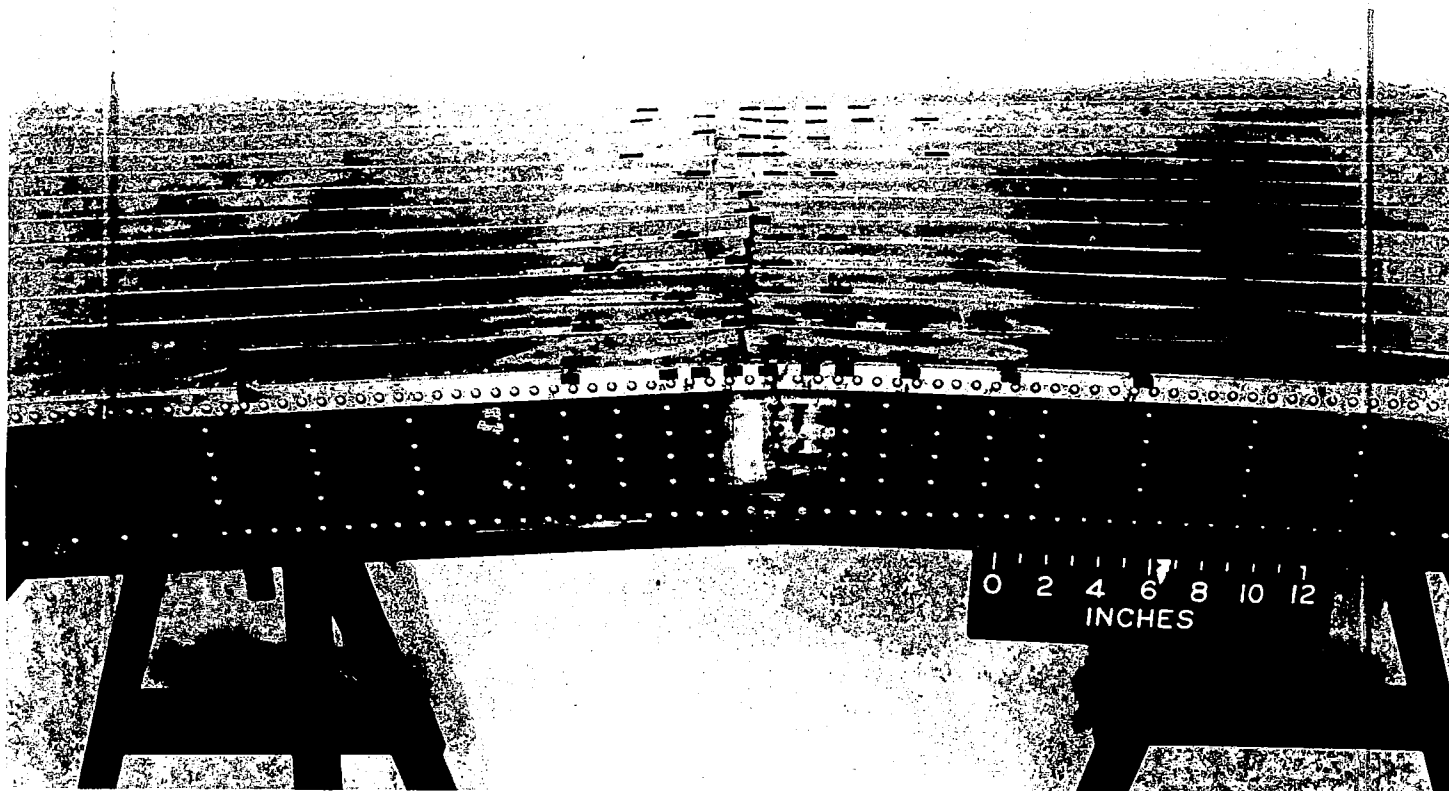


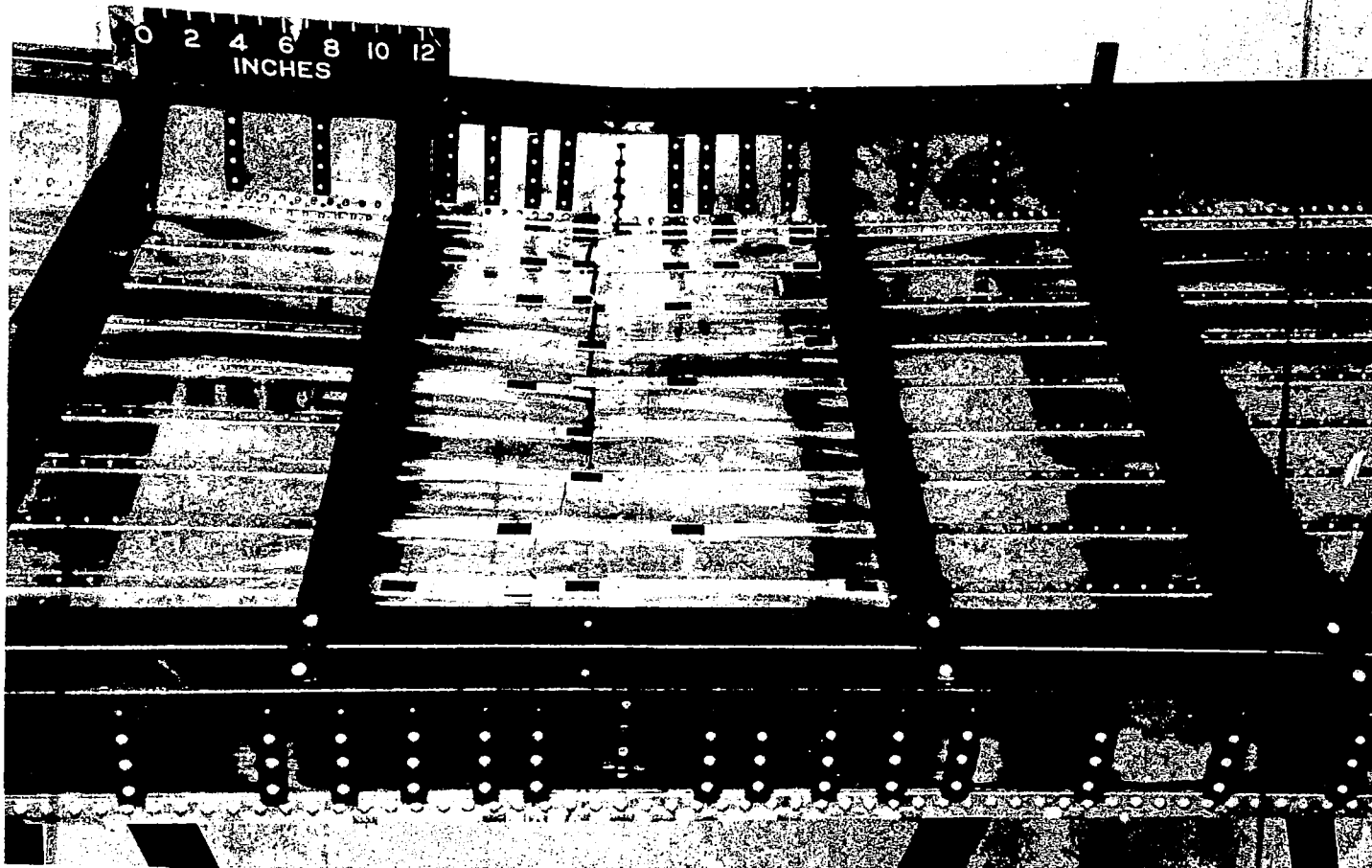
Figure 14.- Strain measurements around rivet holes in auxiliary tension specimen B.





(a) Outside of cover.

Figure 15.- Failure at root of box beam.



(b) Inside of cover. Root bulkhead removed.

Figure 15.- Concluded.

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